NASA Technical Memorandum 81855

NASA-TM-81855 19800021267

EFFECTS OF SUBSTRATE DEFORMATION AND SIP THICKNESS ON TILE/ SIP INTERFACE STRESSES FOR SHUTTLE THERMAL PROTECTION SYSTEM

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July 1980

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SUMMARY

A previously developed nonlinear analysis was used to study the effects of substrate deformation characteristics and strain isolator pad, SIP, thickness on TILE/SIP interface stresses for the Space Shuttle thermal protection system. The configuration analyzed consisted of a 5.08 cm (2 in.) thick 15.24 cm (6 in.) square tile with a 12.7 cm (5 in.) square SIP footprint bordered by a 1.27 cm (0.5 in.) wide filler bar. This configuration was subjected to forces and moments representative of a 20.7 kPa (3 psi) aerodynamic shock passing over the tile. SIP stress-deflection curves used in the study were obtained after a 69 kPa (10 psi) proof load and 100 cycles conditioning at 55 kPa (8 psi). The study showed that TILE/SIP interface stresses increase over flat substrate values for zero-to-peak substrate deformation amplitudes up to 0.191 cm (0.075 in.) by up to a factor of nearly five depending on deformation amplitude, half-wave-length, and location. Stresses for a 0.23 cm (0.09 in.) thick SIP were found to be up to 60 percent greater than for a 0.41 cm (0.160 in.) thick SIP for identical loads and substrate deformation characteristics. Additionally, a simplified method was developed for approximating the substrate location which produces maximum TILE/SIP interface stresses.

INTRODUCTION

Recent tests (ref. 1) have shown that the strain isolator pad (SIP) portion of the Space Shuttle thermal protection system (TPS) has highly nonlinear and load-history dependent stress-deflection characteristics. This nonlinear behavior prevents accurate stress predictions based on a linear analysis, therefore, a nonlinear analysis for stresses at the TPS TILE/SIP interface described in reference 2 was developed and incorporated in an existing computer code (ref. 3). Results from the nonlinear analysis presented in reference 2 indicate that TILE/SIP interface stresses are sensitive to deformations in the Shuttle structure which supports the TILE/SIP combination and stresses predicted by a linear analysis were found to be unconservative for several combinations of loads and substrate structure deformation. The large number of tiles and substrate deformation patterns possible on the Shuttle present a formidable problem for the stress analyst. A tractable way of approaching such a problem is to study the effects of various parameters to determine those with major impact. Thus, the current study was undertaken to determine the influence of substrate deformation and SIP thickness on the static stress response of the TPS. Stresses at the TILE/SIP interface are presented for 0.41 cm (0.160 in.) and 0.23 cm (0.090 in.) thick SIP for various amplitudes and locations of a double cosine substrate deformation pattern representative of buckle patterns over various portions of the Shuttle.

ANALYSIS

The nonlinear analysis presented in reference 2 was used for the current investigation. In the analysis it is assumed that the tile behaves as a rigid body, tile rotations are small and a mismatch exists between the tile and substrate structure which can result from tile imperfections, tile warpage, substrate initial curvature or substrate deformation under load. To account for the nonlinear SIP behavior, the SIP is assumed to behave as a nonlinear continuous spring-type foundation whose experimental stress-deflection curve is input to the computer code as a table. To solve the force and moment equilibrium equations for the rigid tile, numerical integration of the SIP stresses is used with a Newton-Raphson iteration procedure to converge on the vertical displacement and rotations which develop SIP stresses required to balance the applied tile forces and moments.

CONFIGURATION AND TILE LOADS

Since many of the Orbiter tiles are square with nominal dimensions of 15.24 cm by 15.24 cm (6 in. by 6 in.) on a 12.7 cm by 12.7 cm (5 in. by 5 in.) SIP footprint, the effects of substrate deformation amplitude and location relative to the tile were determined for such tiles. The configuration studied is shown in figure 1 for a 5.08 cm (2 in.) thick tile. Effects of the 1.27 cm (0.5 in.) wide filler bar around the tile perimeter used to form a seal between tiles were included in the calculations. The filler bar is attached to the substrate only and therefore supports compressive loads only. Stress-deflection curves for both 0.41 cm (0.160 in.) thick and 0.23 cm (0.090 in.) thick SIP obtained after a 69 kPa (10 psi) proof load and 100 cycles of conditioning at 55 kPa (8 psi) were used for the calcuations and are shown in figure 2.

A double-cosine substrate deformation pattern oriented along the tile diagonal with a single half wave in the y-direction and multiple half waves in the x-direction was considered in the study. Figure 3 shows the variation of the substrate deformation half-wave-lengths. For the single wave in the y-direction the half-wave-length was constant at 17.96 cm. (7.07 in.). In the x-direction the half-wave-length was varied from 4.5 cm to 17.96 cm (1.77 in. to 7.07 in.). The zero-to-peak substrate deformation amplitude was varied from 0 to 0.191 cm. (0 to 0.075 in.).

As shown in figure 4, loads on the tile were derived from a 20.7 kPa (3 psi) sharp edge aerodynamic shock moving diagonally across the tile. The passing shock creates a low pressure region over the tile which causes tensile forces and moments to develop over the tile surface as air trapped in the porus tile and SIP is vented. An existing Shuttle tile configuration with a substrate deformation of 0.18 cm (0.070 in.) zero-to-peak amplitude and half-wave-lengths of 5.26 cm (2.07 in.) in the x-direction and 17.15 cm (6.75 in.) in the y-direction was used to determine representative tile loads. The shock position was adjusted until a maximum interface tensile stress was obtained. For this position the shock introduced a tensile load of 364.7 N (82 lb.) and moments of $-M_x = M_y = 3.15$ N m (28 lb.-in.) at the tile center of gravity.

RESULTS AND DISCUSSION

Substrate Deformation Characteristics

Effects of amplitude and half-wave-length. - Figure 5 shows maximum through-the-thickness stresses at the TILE/SIP interface as a function of substrate deformation half-wave-length. Results are shown for zero-to-peak amplitudes of 0, 0.064, 0.127, and 0.191 cm (0, 0.025, 0.050, and 0.075 in.) with the maximum downward substrate deflection located at the SIP corner. As the half-wave-length decreases the TILE/SIP interface stresses increase from values comparable to a flat substrate to peak values which are three to four times greater depending on the deformation amplitude at a half-wave-length of about 6.35 cm (2.5 in.).

Effects of location. - Since it is unlikely that the maximum substrate deformation depth will always occur at the SIP corner, the effects of shifting the deformation shape along the direction of the tile diagonal were investigated. For each half-wave-length value investigated the deformation shape was shifted as shown in figure 6 so that the position of the maximum downward deformation moved to the right (+) or left (-) away from the left SIP corner, and interface stresses were calculated. This process is illustrated in figure 7 which shows maximum TILE/SIP interface stresses as a function of maximum deformation amplitude position for a half-wave-length of 8.99 cm (3.54 in.) and zero-to-peak amplitude of 0.064 cm (0.025 in.). For this example maximum stresses occurred at the SIP corners. This was usually the case although for some half-wave-lengths and substrate deformation locations maximum stresses were obtained away from the SIP corners. The results in figure 7 show that by shifting the substrate deformation from the SIP corner 2.54 cm (1 in.) in the positive x direction the maximum SIP stresses occur at the right SIP corner and by shifting it from the SIP corner 2.54 cm (1 in.) in the negative x direction maximum stresses occur at the left corner. Movement in the negative x direction results in the greatest SIP tensile stresses. The mechanism responsible for this behavior is illustrated in figure 8 which shows stress distributions along the tile diagonal corresponding to the two locations which produce maximum stresses at the SIP corners (+ 2.54 cm (+1 in.)). For the loads considered, the upward portion of the substrate deformation prevents large areas of the SIP footprint from experiencing displacements sufficient to generate significant tensile stresses to help react the applied force and moments. As the deformation is shifted in the positive x direction a large area exists to the left of the tile center of gravity which can build up significant tensile forces; however, as the deformation is shifted to the left this area is reduced and greater stresses must be developed on the left side to equilibrate the applied forces.

Figure 9 shows the location of the maximum substrate deformation amplitude which results in maximum tensile interface stresses in the SIP as a function of substrate deformation half-wave-length. The longer half-wave-lengths require the greatest shift to move the upward portion of the substrate deformation to the left of the tile center of gravity. For the shorter half-wave-lengths(less than about 7 cm. (2.75 in.)) located with the

maximum downward deformation at the left SIP corner, significant portions of the SIP to the left of the center of gravity experience an upward deformation (see fig. 3), and maximum TILE/SIP interface stresses occur for very small shifts of the substrate deformation.

Maximum TILE/SIP interface stresses obtained by shifting the substrate deformation are shown as a function of half-wave-length in figure 10. For comparison, stresses obtained for the maximum downward substrate deformation located at the SIP corner are also shown. For the shorter half-wave-lengths (less than about 7.6 cm (3 in.)) the effect is small and increases the stress by only about 15 percent; however, for the longer half-wave-lengths the stresses can be increased by a factor of 2 or greater. Thus, it appears that substrate deformation location is a very important parameter in determination of maximum TILE/SIP interface stresses for areas on the vehicle which experience buckle half-wave-lengths longer than about 7.6 cm (3 in.)

Approximate Maximum Stress Location

Since the maximum TILE/SIP interface stresses are a function of the SIP area available to resist tensile stresses introduced by the applied forces, a simplified way to approximate the substrate location for maximum stresses consists of the following:

(1) Position the SIP footprint over the deformation planform so that SIP regions which experience tension loads from the applied moments are compressed by the substrate deformation.

(2) Calculate the area compressed by the substrate deformation and shift the substrate location until the compressed area reaches a maximum.

(3) The substrate deformation location which compresses the maximum SIP area gives interface stresses that are close to actual maximum values.

For example, figure 11 shows the deformation planform for a half-wave-length of 8.99 cm (3.54 in.) and the SIP footprint for two positions. For position 1, maximum downward deformation at the left SIP corner, only the SIP area bounded by lines A and B is compressed by the substrate. For position 2, maximum downward deformation shifted 4.5 cm (1.77 in.) to the left of the SIP corner, the entire SIP area to the left of the tile center of gravity is compressed (region between lines A and C). From figure 7 this location results in a maximum interface stress of 128 kPa (18.3 psi) compared to the actual value of 136 kPa (19.7 psi). Figure 12 shows a comparison of maximum TILE/SIP interface stresses generated by this approach with results for the calculated maximum stresses from figure 10. The two calculations agree rather well with a difference of usually less than 5 percent.

Effects of SIP Thickness

To see if the 0.23 cm (0.090 in.) thick SIP is less sensitive to substrate deformation characteristics than the 0.41 cm (0.160 in.) thick SIP, identical calculations to those for figure 10 were made for the 0.23 cm (0.090 in.) SIP stress-deflection curve. Figure 13 shows a comparison of maximum TILE/SIP interface stresses for the two SIP thicknesses as a function of half-wave-length for zero-to-peak amplitudes of 0, 0.064, and 0.127 cm (0,0.025, and 0.050 in.). These results indicate that for a flat substrate the stiffer 0.23 cm (0.090 in.) SIP has lower stresses than the 0.41 cm (0.160

in.) SIP; however, the presence of substrate deformation causes significantly higher stresses (about 60 percent greater for peak values at a zero-to-peak amplitude of 0.127 cm (0.050 in.)) in the thinner SIP for identical loads and substrate deformation characteristics. Thus the 0.23 cm (0.090 in.) SIP appears attractive only in regions which are nearly flat because of its higher allowable stress.

CONCLUDING REMARKS

Effects of substrate deformation amplitude, half-wave length, and location and two SIP thickness on TILE/SIP interface through-the-thickness stresses were studied using a previously developed nonlinear analysis. The configuration studied consisted of a 5.08 cm (2 in.) thick square tile 15.14 cm (6 in.) on a side with a 12.7 cm (5 in.) square footprint bordered by a 1.27 cm (0.5 in.) wide filler bar. The tile was subjected to forces and moments generated by a 20.7 kPa (3 psi) aerodynamic shock passing over the tile. Stress-deflection curves for both SIP thicknesses obtained after a 69 kPa (10 psi) proof load and 100 cycles conditioning at 55 kPa (8 psi) were used in the calculations.

From these calculations it may be concluded that for zero-to-peak substrate deformation amplitudes of up to 0.191 cm (0.075 in.), TILE/SIP interface stresses:

1. Increase by up to a factor of four over flat substrate values as the substrate deformation half-wave-length decreases from 17.8 to 5.08 cm (7 to 2 in.) depending on the deformation depth.
2. Increase by up to a factor of two for half-wave-lengths greater than 7.6 cm (3 in.) depending on the location of the substrate deformation maximum depth.
3. Are up to 60 percent greater in the 0.23 cm (0.090 in.) thick SIP than in the 0.41 cm (0.160 in.) thick SIP for identical loads and substrate deformations.

Additionally, a simplified method was developed for rapidly determining the worst case distribution of substrate deformation. Use of the method resulted in interface stresses which were usually within five percent of maximum values.

It should be noted that because of the SIP nonlinearity these conclusions apply only for the parameter ranges considered and should not be extrapolated beyond those limits.

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3. Giles, Gary L.; and Vallas, Maria: Computer Program for Nonlinear Static Stress Analysis of Shuttle Thermal Protection System-Users Manual. NASA TM 81856, July, 1980.

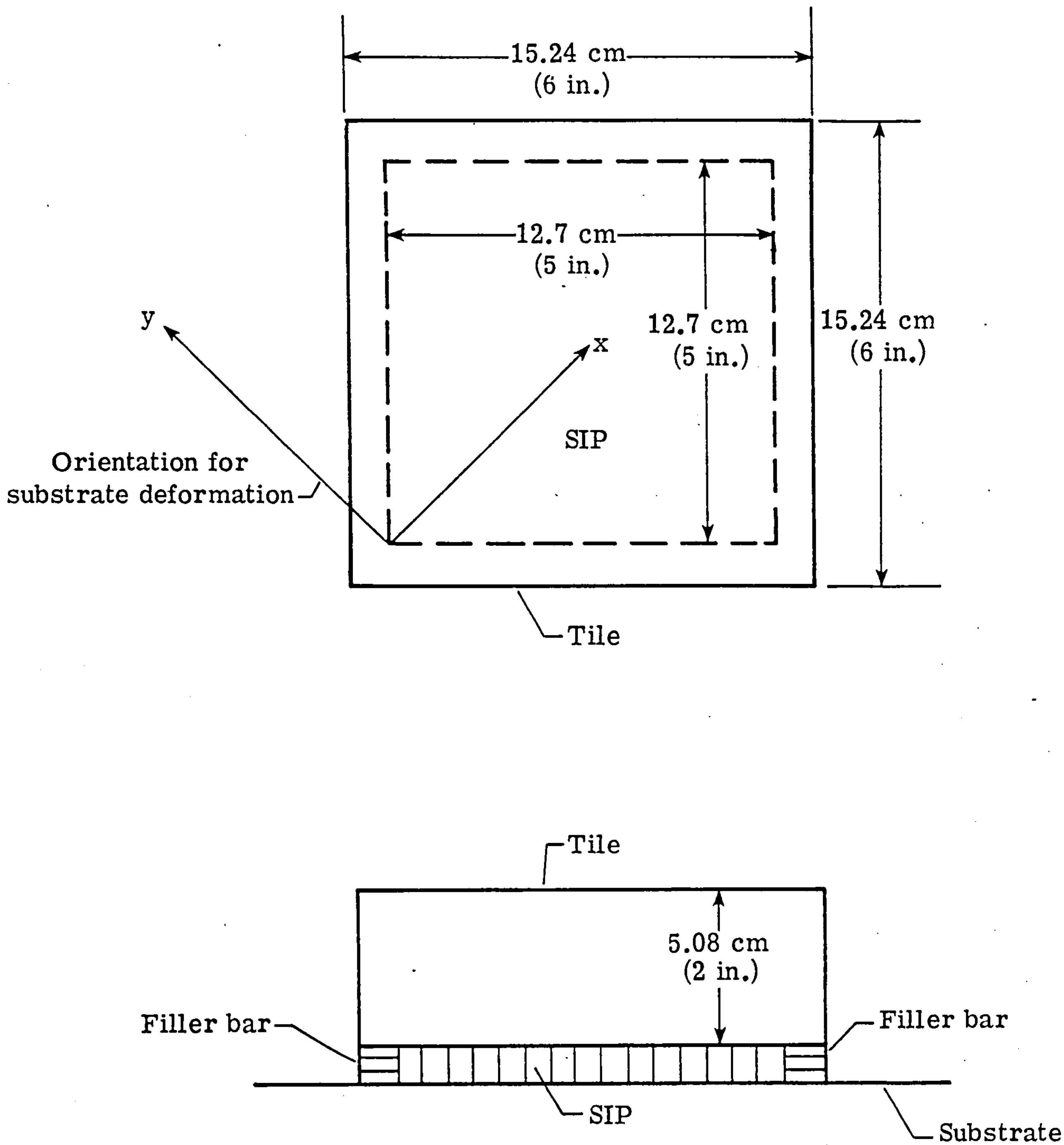


Figure 1.- TPS configuration.

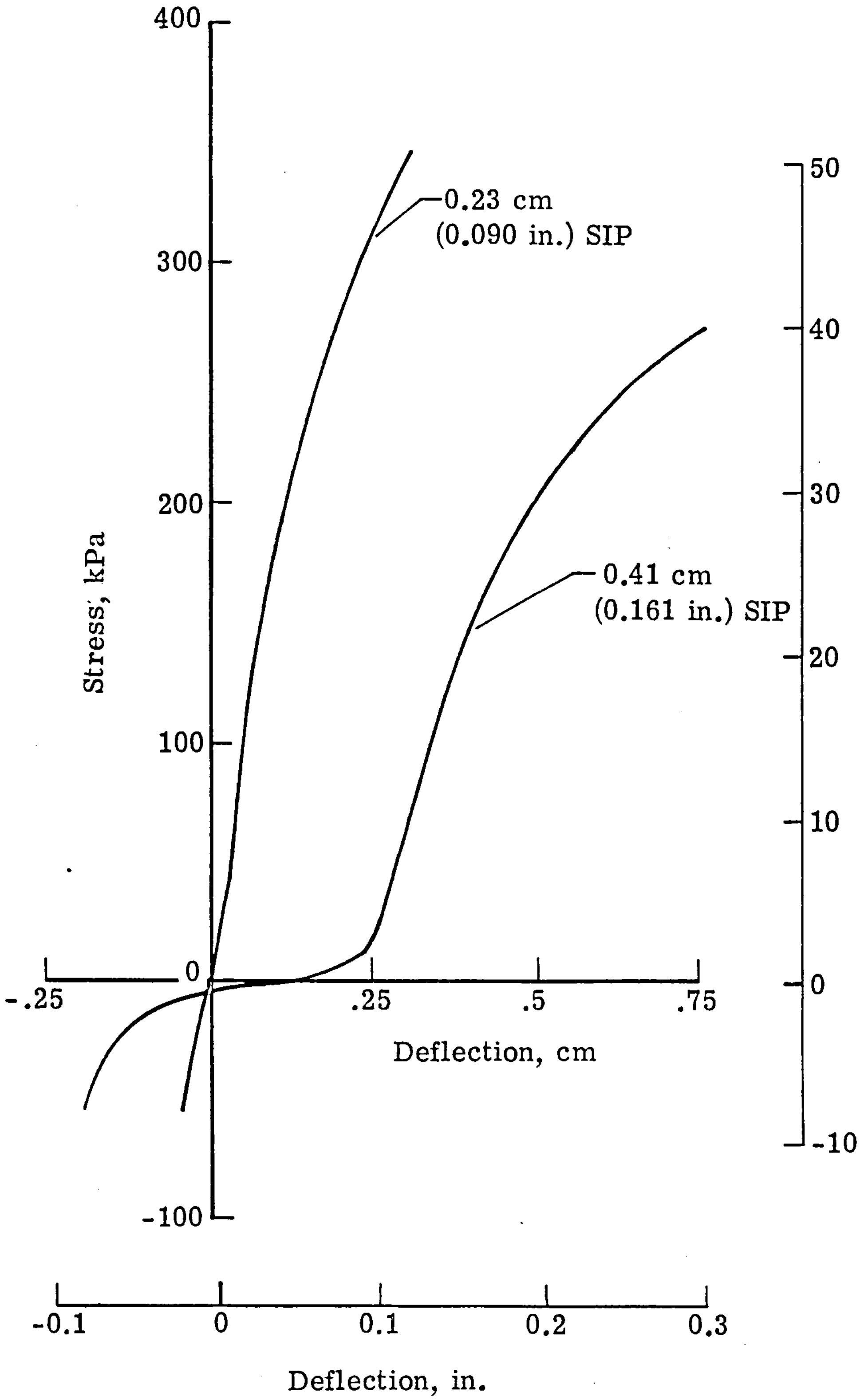
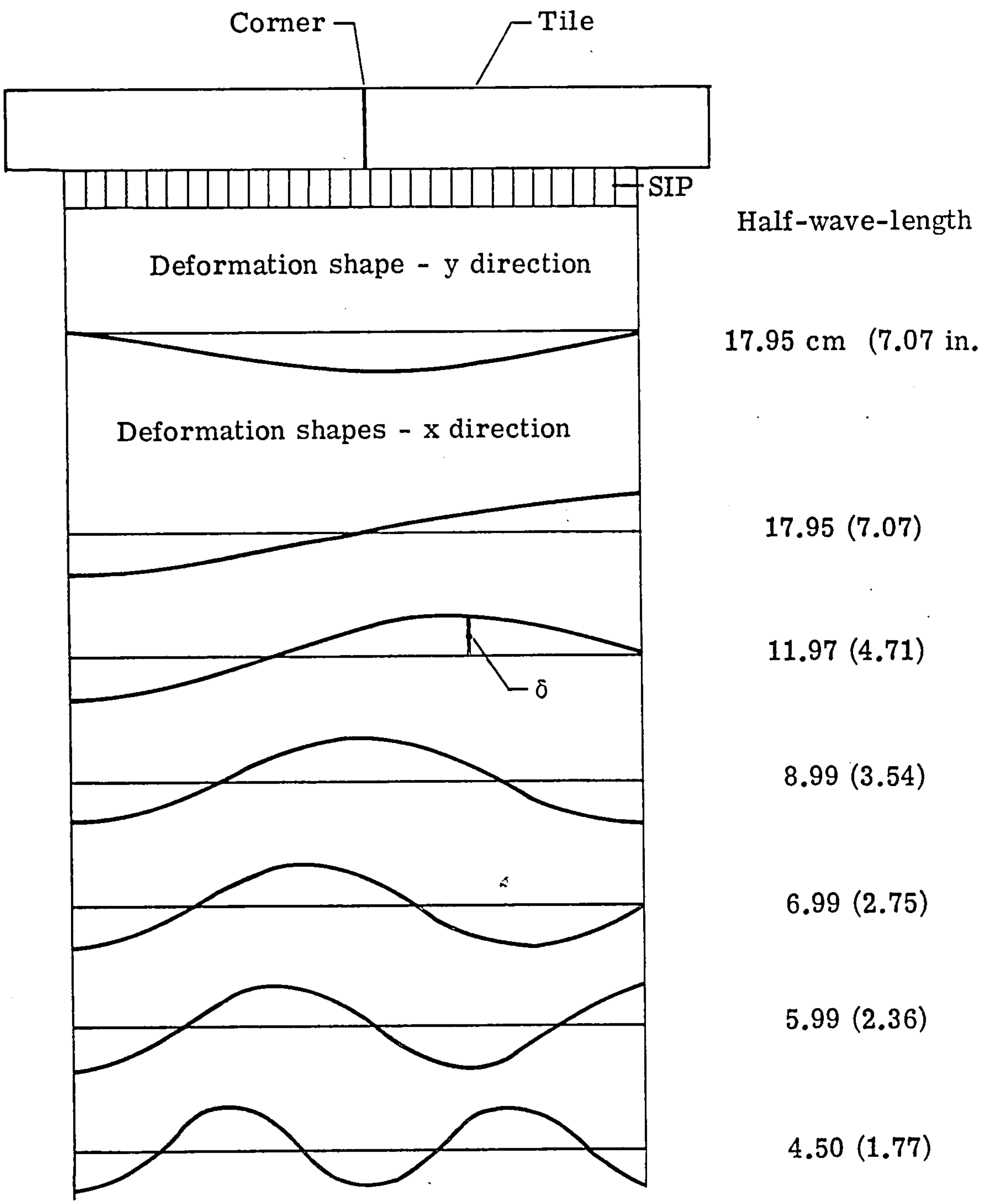


Figure 2.- SIP stress-deflection curves.



δ = 0, 0.064, 0.127, 0.191 cm
0, 0.025, 0.050, 0.075 in.

Figure 3.- Substrate deformation characteristics.

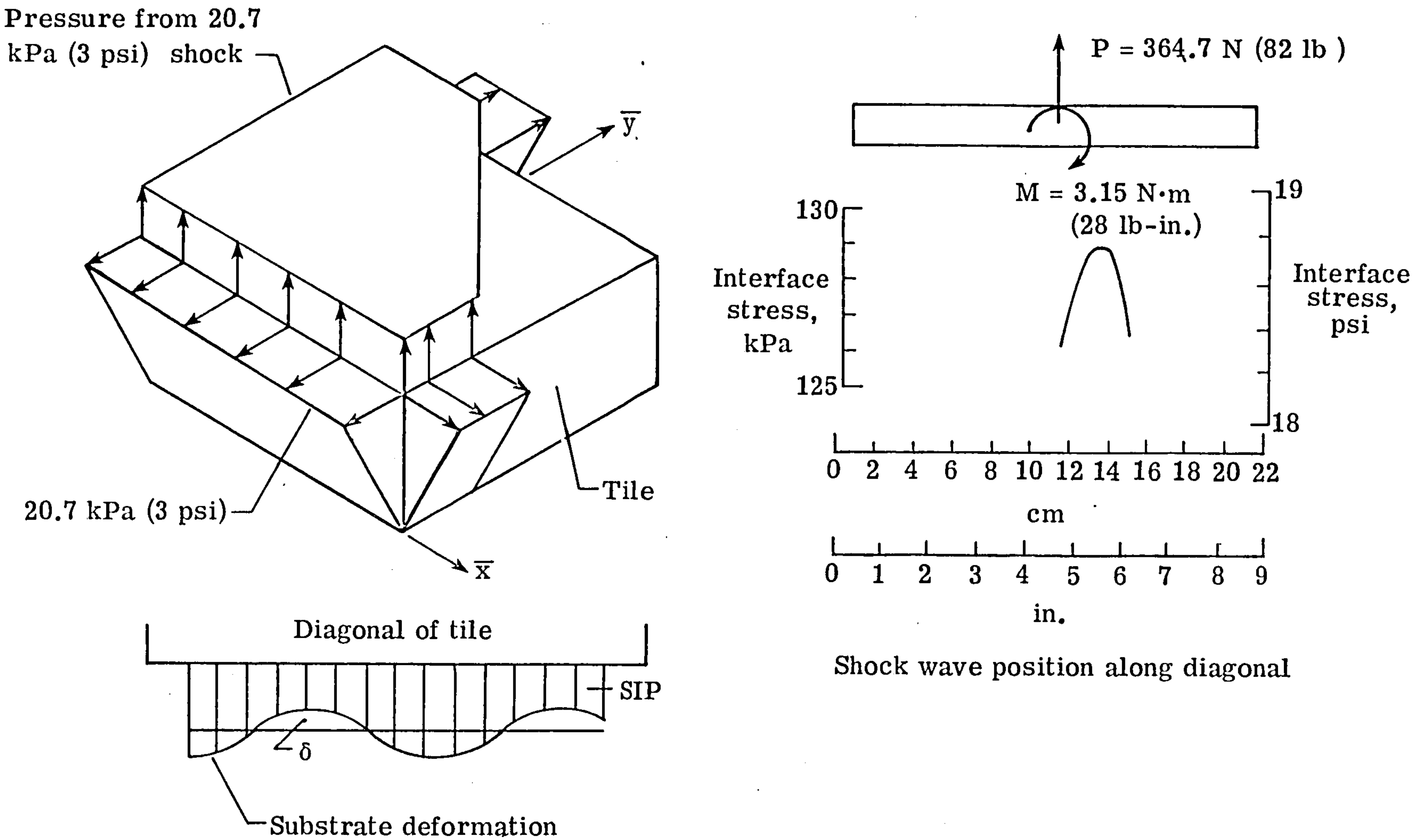


Figure 4.- Tile loads derivation.

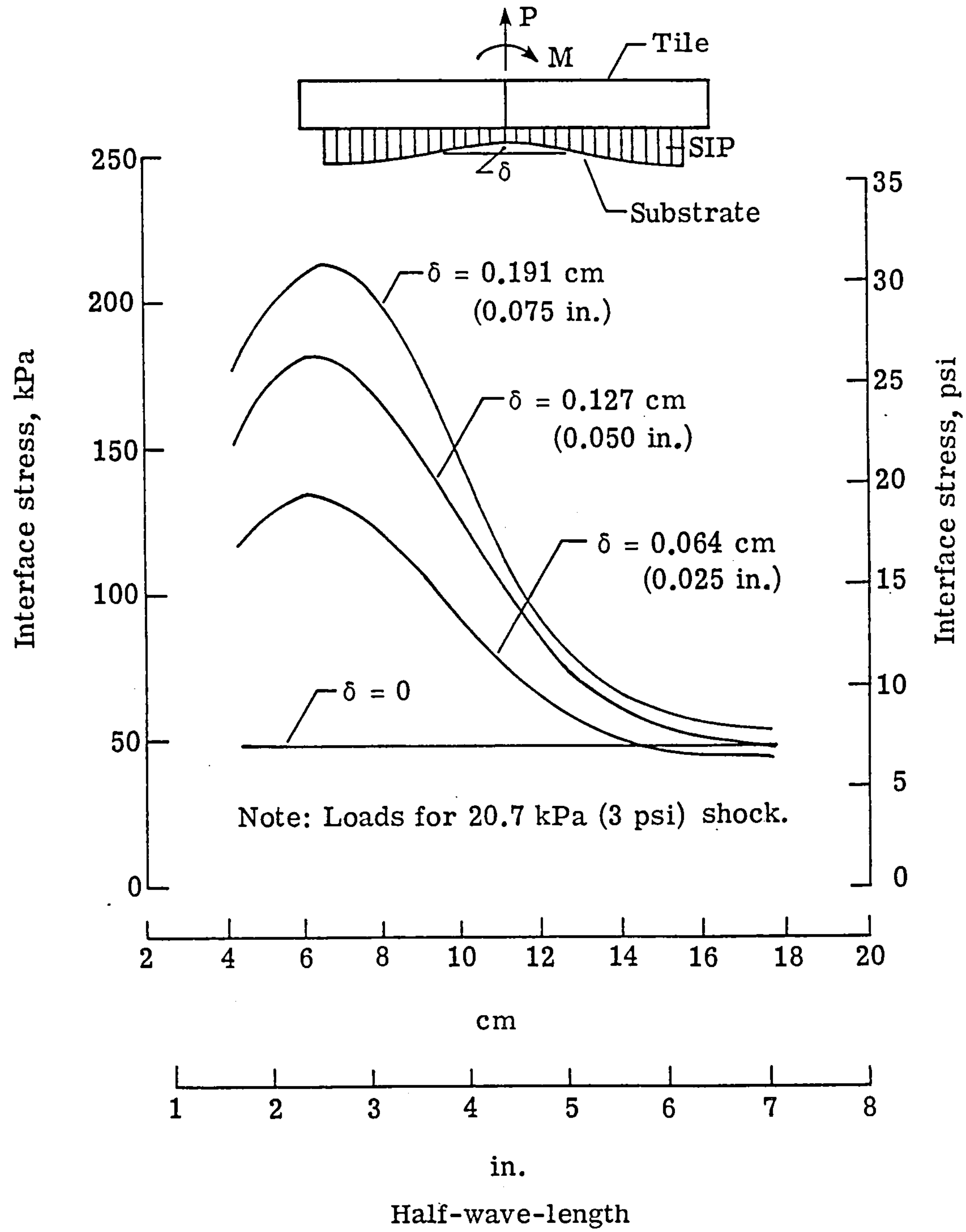
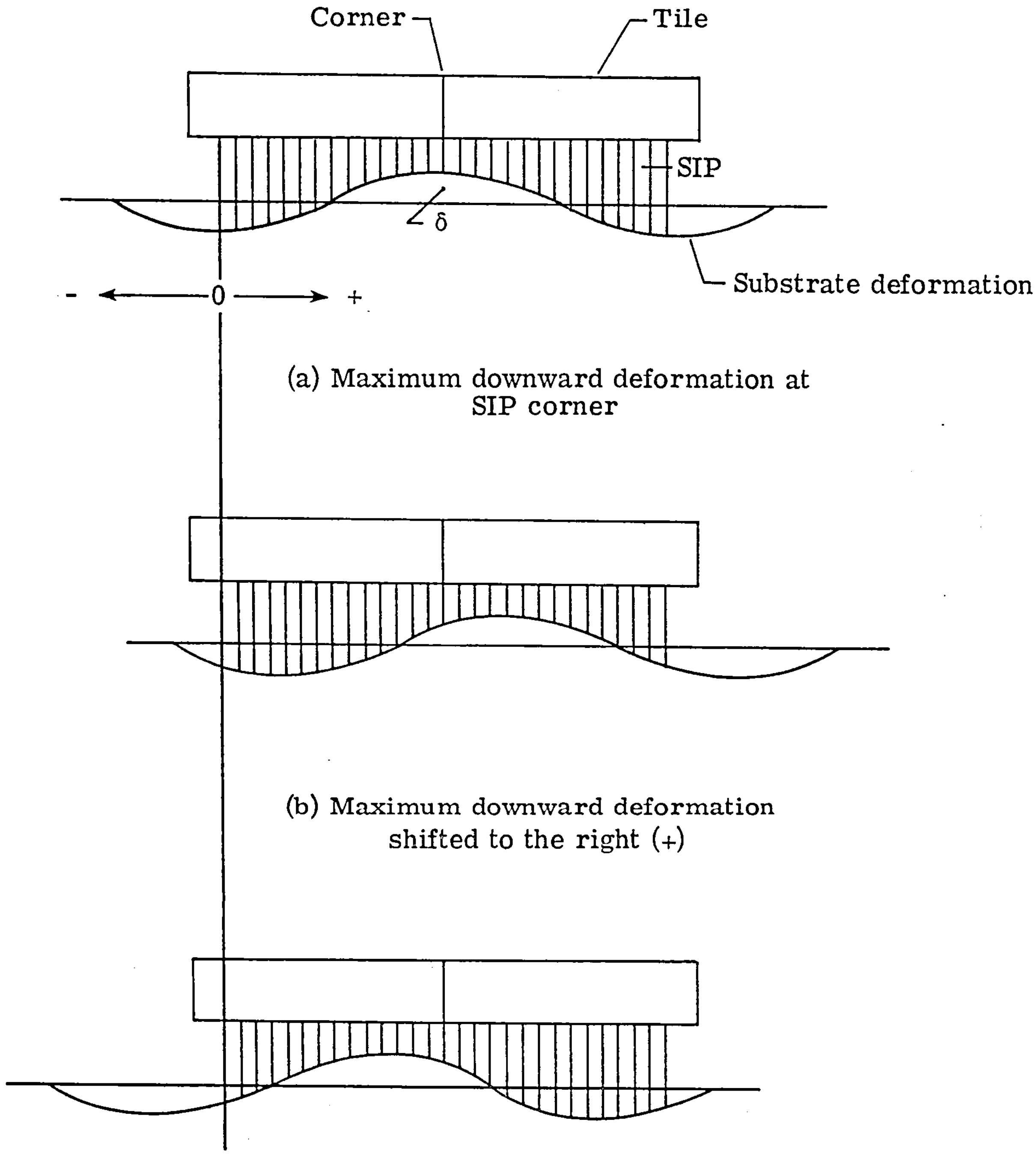


Figure 5.- Effects of substrate deformation amplitude and half-wave-length on through-the-thickness TILE/SIP interface stresses.

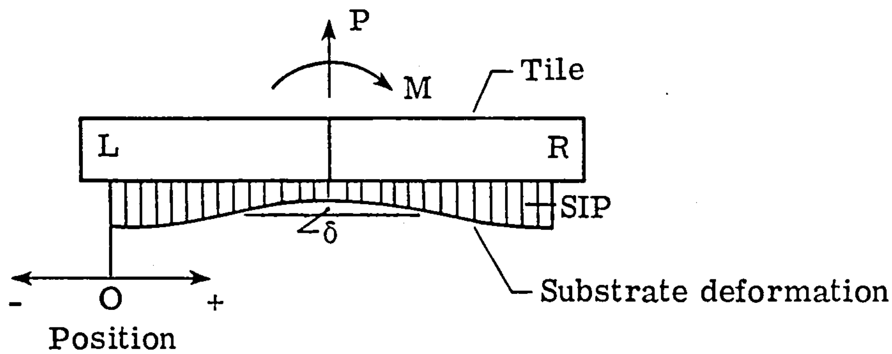


(a) Maximum downward deformation at SIP corner

(b) Maximum downward deformation shifted to the right (+)

(c) Maximum downward deformation shifted to the left (-)

Figure 6.- Co-ordinate for locating substrate deformation from SIP corner.



Note: Loads for 20.7 kPa (3 psi) shock.

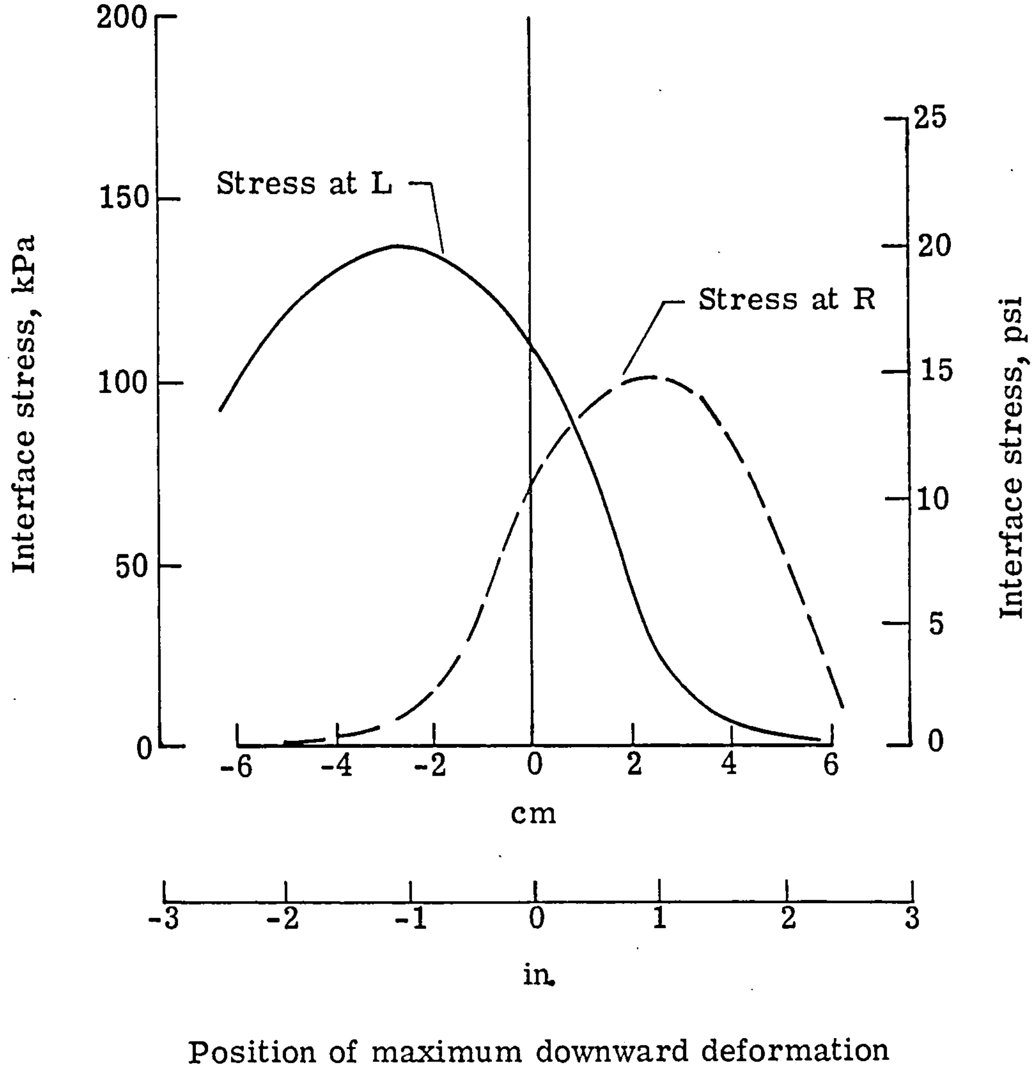


Figure 7.- Effect of substrate deformation location on TILE/SIP interface stresses at SIP corners for δ = 0.064 cm(0.025 in.) and half-wave-length of 8.99 cm(3.54 in.).

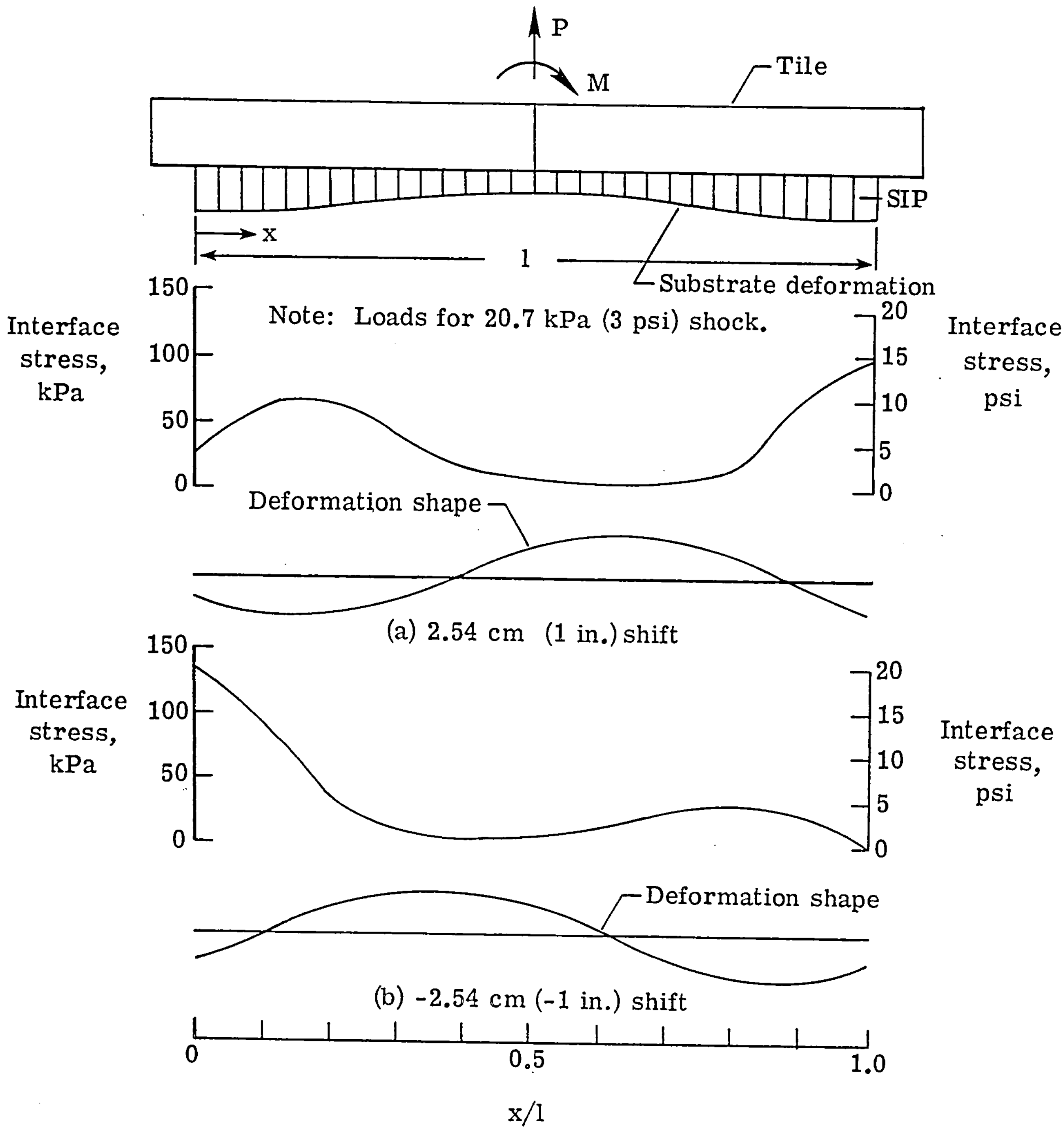


Figure 8.- Effect of substrate deformation location on TILE/SIP interface stress distribution along tile diagonal for δ = 0.064 cm(0.025 in.) and half-wave-length of 8.99 cm(3.54 in.).

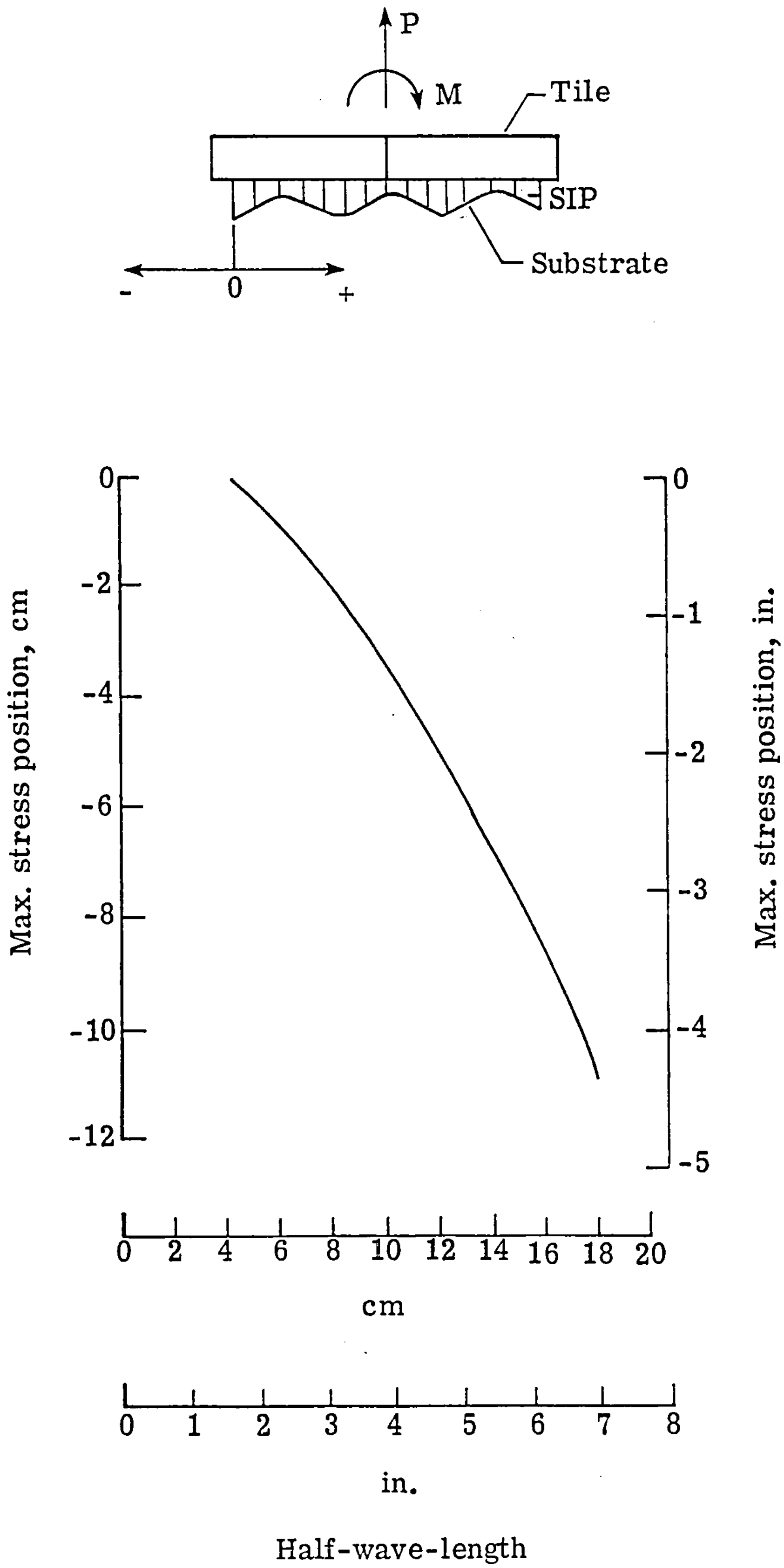


Figure 9.- Substrate deformation locations for maximum TILE/SIP interface stresses.

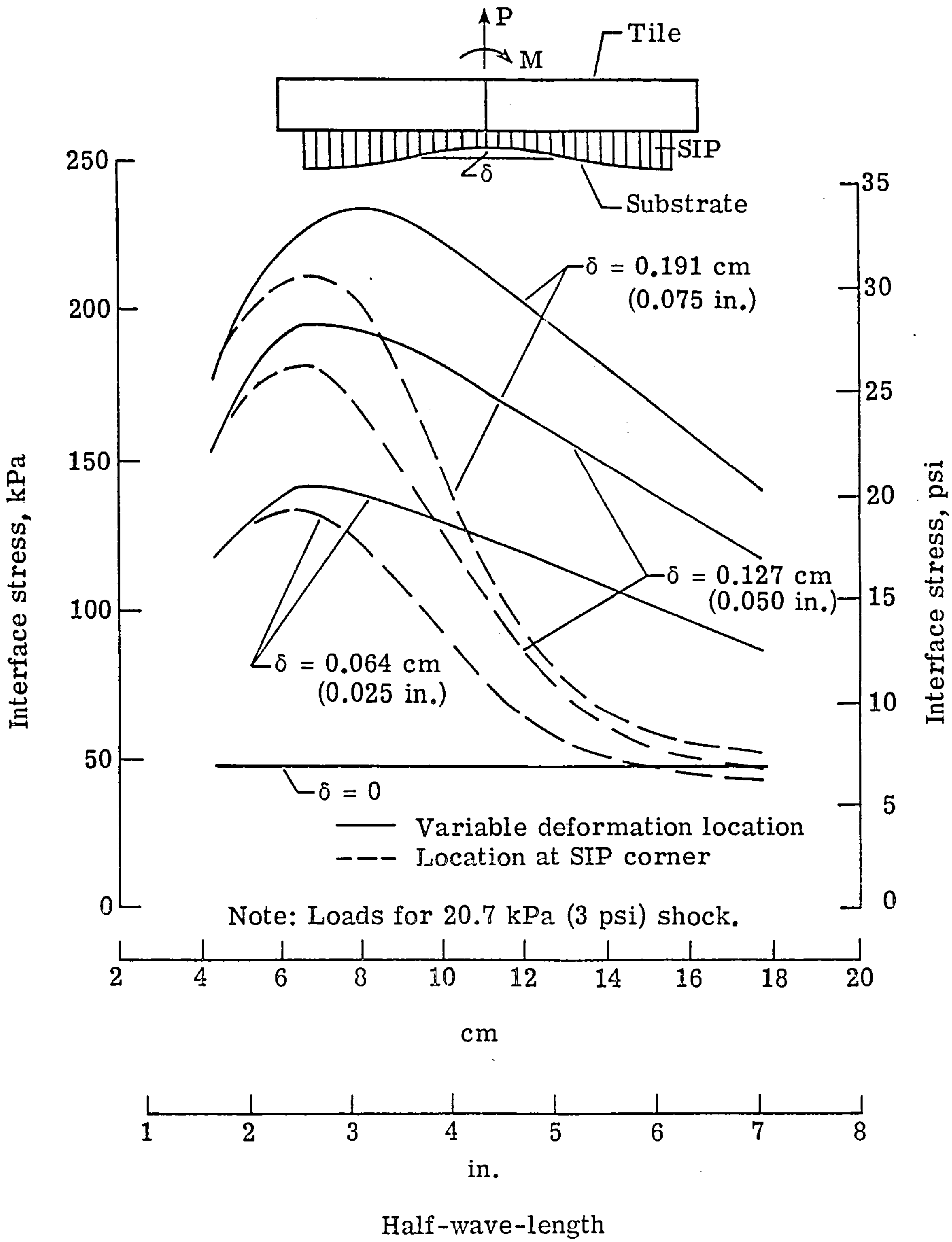


Figure 10.- Effects of substrate deformation amplitude, half-wave-length, and location on maximum TILE/SIP interface stresses.

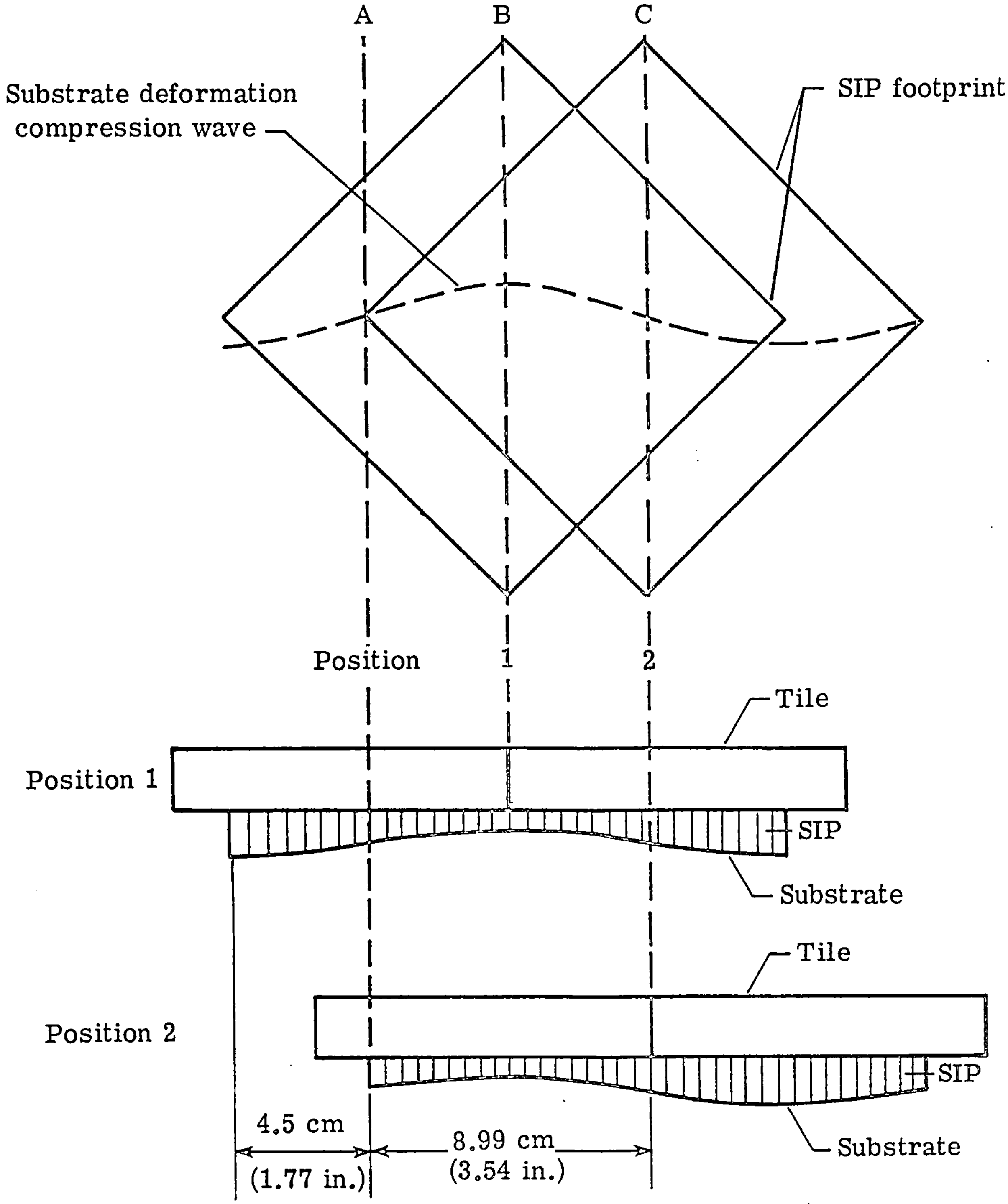


Figure 11.- Determination of substrate deformation location for approximate maximum interface stresses.

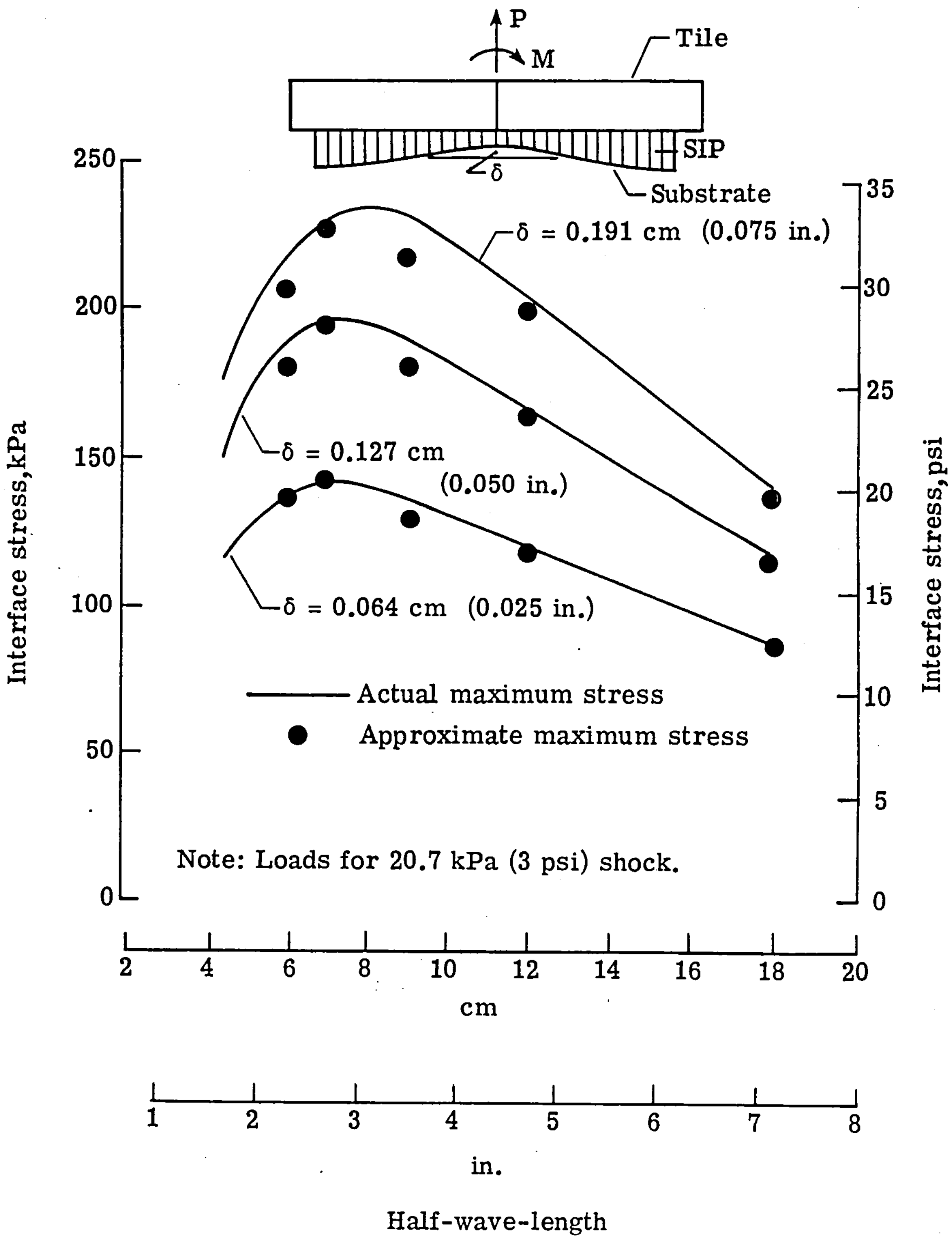


Figure 12.- Comparison of actual with approximate maximum TILE/SIP interface stresses.

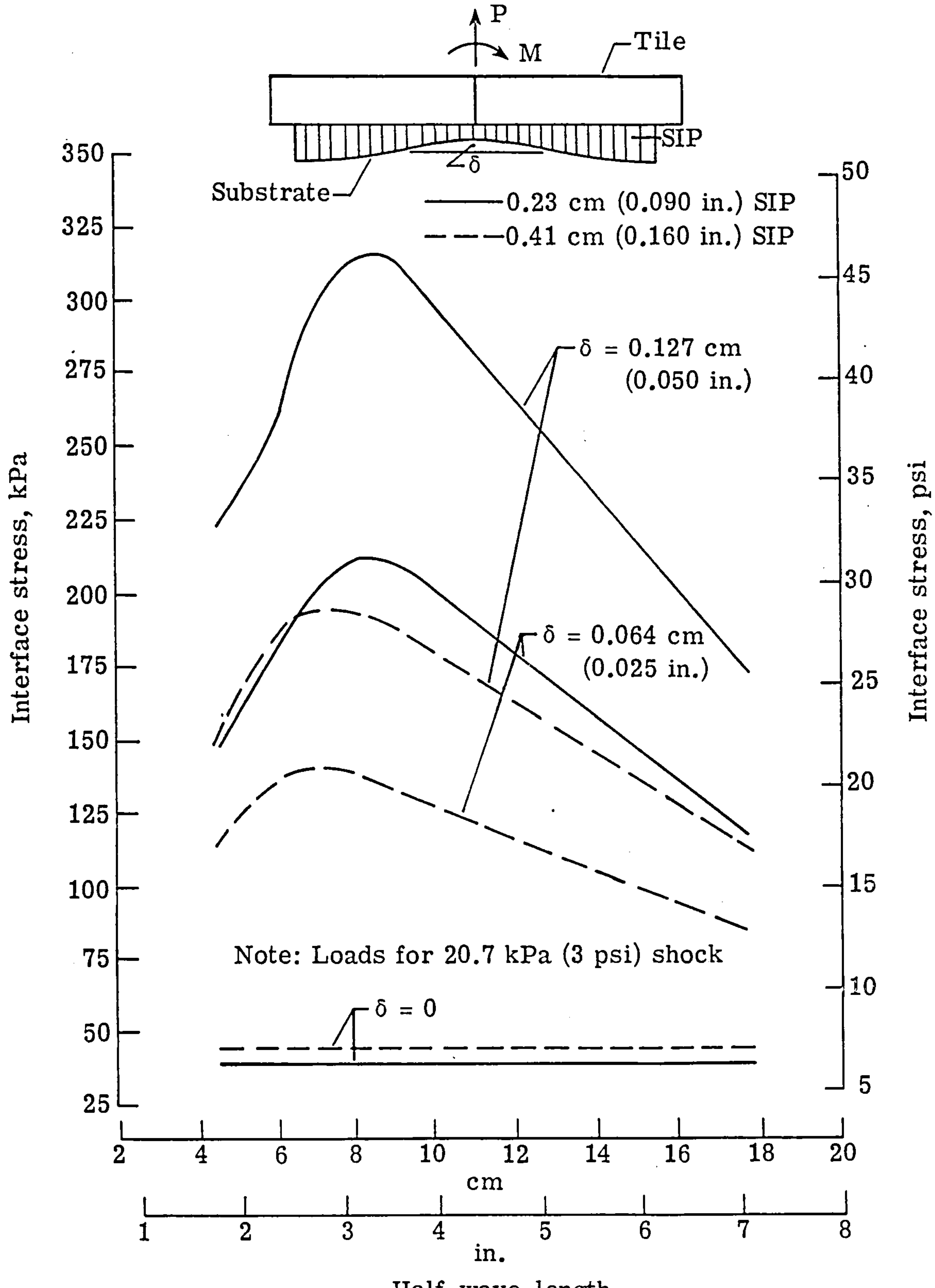


Figure 13.- Comparison of maximum TILE/SIP interface stresses for 0.23 cm(0.090 in.) and 0.41 cm(0.160 in.) thick SIP.

1. Report No. NASA TM-81855	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Effects of Substrate Deformation and SIP Thickness on Tile/SIP Interface Stresses for Shuttle Thermal Protection System		5. Report Date July 1980
		6. Performing Organization Code
7. Author(s) Charles P. Shore and Ramon Garcia		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A previously developed nonlinear analysis was used to study the effects of substrate deformation characteristics and strain isolator pad, SIP, thickness on TILE/SIP interface stresses for the Space Shuttle thermal protection system. The configuration analyzed consisted of a 5.08 cm (2 in.) thick 15.24 cm (6 in.) square tile with a 12.7 cm (5 in.) square SIP footprint bordered by a 1.27 cm (0.5 in.) wide filler bar. This configuration was subjected to forces and moments representative of a 20.7 kPa (3 psi) aerodynamic shock passing over the tile. SIP stress-deflection curves used in the study were obtained after a 69 kPa (10 psi) proof load and 100 cycles conditioning at 55 kPa (8 psi). The study showed that TILE/SIP interface stresses increase over flat substrate values for zero-to-peak substrate deformation amplitudes up to 0.191 cm (0.075 in.) by up to a factor of nearly five depending on deformation amplitude, half-wave-length, and location. Stresses for a 0.23 cm (0.09 in.) thick SIP were found to be up to 60 percent greater than for a 0.41 cm (0.160 in.) thick SIP for identical loads and substrate deformation characteristics. Additionally, a simplified method was developed for approximating the substrate location which produces maximum TILE/SIP interface stresses.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Thermal Protection System Shuttle TPS Nonlinear Stress Analysis	Unclassified - Unlimited Subject Category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	19	A02

N-305